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Full Length Research Paper

A review of design specifications of opening in the web for simply supported RC beams

Soroush Amiri*, Reza Masoudnia and Mohammad Amin Ameri

Department of Civil and Structural Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Selangor, Malaysia.

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The present study reviews the design specifications of openings in the web for simply supported reinforced concrete (RC) beams and rectangular concrete beams conducted by previous researchers. A number of papers have been found to handle the reinforced concrete beams containing a series or isolated web openings. The effects of the size and location of the openings on the behavior of such beams are examined and the strengths of these openings are investigated as well. This paper, therefore, discusses and describes the previous researches which are related to the openings in the web of reinforced concrete (RC) beams.

Key words: Web opening, design procedure, reinforced concrete beams.

INTRODUCTION

In order to save headroom in buildings, and optimize the required storey height in buildings, beams are provided with openings in the web for the passage of service ducts. Because of the limited depth of the RC beams, introducing the opening in these beams is very significant therefore; this study is going to review the work has that been done by other researchers, since very limited data have been reported on design specifications of concrete beams with web opening.

OVERVIEW OF THE RESEARCH

On the basis of some experimental studies, several design equations for normal and lightweight concrete deep beams with web openings were introduced by Kong and Sharp (1977) and Kong et al. (1970, 1973, 1998). The ultimate shear strength equations for reinforced concrete deep beams are: for solid deep beam, and

$$Q = c_1\left[1 - 0.35\frac{x}{D}\right]f_t bD + c_2\sum a\frac{y}{D}\sin^2\alpha_1 \quad (1)$$

for solid deep beam, and

$$Q = c_1\left[1 - 0.35\frac{k_1 x}{k_2 D}\right]k_2 f_t bD + c_2\sum \lambda c_2 a\frac{y}{D}\sin^2\alpha_1 \quad (2)$$

for deep beam with web opening

Where;
c_1 = Empirical coefficient (1.40 for normal strength concrete, 1.35 for light weight concrete); b = width of the beam; D = Overall depth; f_t = Cylinder-splitting tensile strength of the concrete; x = Clear-shear-span distance; c_2 = Empirical coefficient (300 N/mm^2 for deformed steel bar, 130 N/mm^2 for plain steel bar); y = Depth at which a typical bar intersects the potential critical diagonal crack in solid deep beam, which is approximately at the line joining the loading and reaction points and; λ = An empirical coefficient, equal to 1.5 for web bars and1.0 for main bars. Other geometric notations are described in Figure 1.

The first term on the right side of the second equation shows the load capacity of strut. The first term also considers the lower load path when an opening is in the natural loading path. The second term on the right side of the equation articulates the contribution of reinforcement in deep beams. It is worthwhile mentioning that these equations are only applicable for the concrete strength less than 46 MPa.

Smith and Vantsiotis (1982) carried out several laboratory tests over deep beams to recognize the contributions

*Corresponding author. E-mail: soroush.amiri@yahoo.com.
Tel: +60-14-2616152.

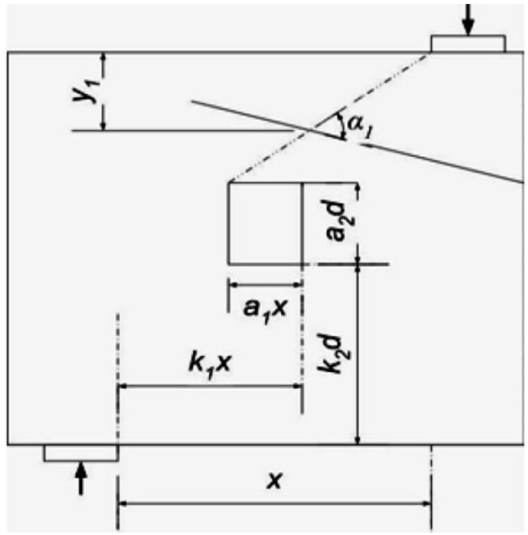


Figure 1. Notation for size and location of opening (Kong et al., 1978).

of web reinforcement upon changing the a/d ratio. They concluded that the minimum reinforcement ratio should be greater than 0.18 and 0.23 for vertical and horizontal reinforcement respectively, and the contribution of web reinforcement cannot exceed $4\sqrt{f_c^{'}}bd$. However, the clear span to depth ratio of the tested beams was between 0.77 and 1.34 which were much less than the ratios suggested by AS3600-01 (The Australian Standard).

Mansur et al. (1992) examined the deflection of reinforced concrete beams with web openings. They intended to develop a simple method for predicting the service load deflection of reinforced concrete beams that contain a large opening in the web. Considering this fact that the point of contraflexure occurs at mid-span of the chord members during the process of loading, deflection Δ caused by a unit load for box structure is given by them as below:

$$\Delta = \frac{l_e^{3}}{12E(I_t + I_b)} \quad (3)$$

In which I_t and I_b are the moments of inertia for top and bottom chords, respectively.

The corresponding deflection caused by shearing deformation of the uniform continuous medium is:

$$\Delta = \frac{l_e}{(GA)_{eq}} \quad (4)$$

The GA parameter of the equivalent continuous medium is then obtained from Equation 3 and 4 as:

$$(GA)_{eq} = \frac{12E(I_t + I_b)}{l_e^{2}} \quad (5)$$

FACILITATION OF SELECTING THE SIZE AND LOCATION OF THE WEB OPENINGS

Kiang-Hwee and Mansur (1996) proposed a simple design procedure for reinforced concrete beams with large web openings. The openings should be provided so that chords have enough concrete area to develop the ultimate compression block in flexure and sufficient depth to provide efficient shear reinforcement. They should not be deeper than one-half the beam depth and should be located not closer than one-half the beam depth from supports or concentrated loads. In continuous beams that generally occur in practice, reduction in stiffness due to the provision of opening through webs causes a redistribution of internal forces and moment, the amount of which needs to be evaluated before a design can proceed. Based on the review of literature on the behavior and strength of the beams with web openings, the following guidelines can be introduced to facilitate the selection of the size and location of the web openings (Figure 2).

For T-beams, openings should preferably be positioned flush with the flange for ease in construction. In the ease of rectangular beams, openings are generally positioned at mid-depth of the section; however, they may also be placed eccentrically with respect to depth. The sufficient concrete cover should be provided for the reinforcement of the chord members above and below the openings. The compression chords should also have enough concrete area to develop the ultimate compression block

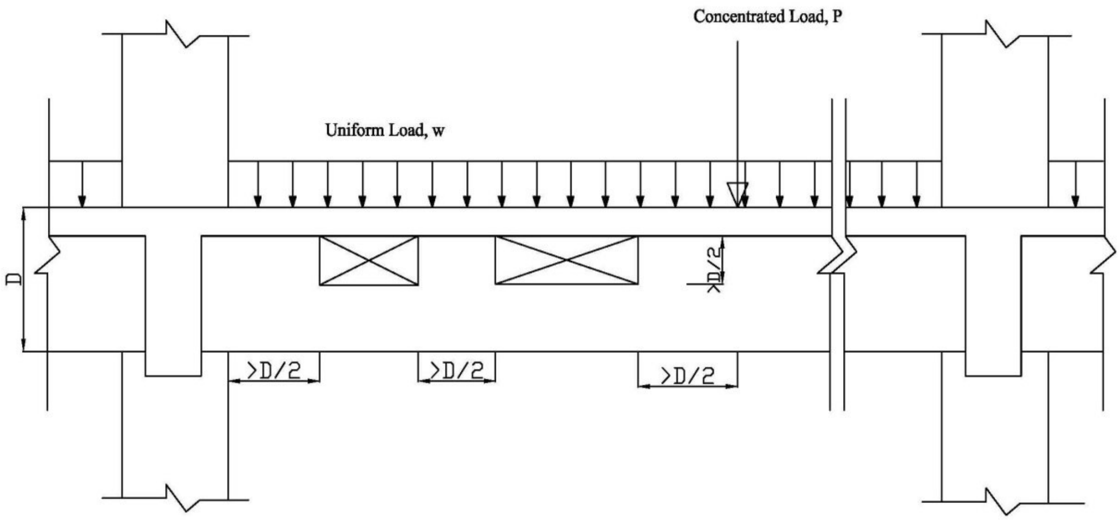


Figure 2. Guidelines for location of the web openings (Kiang-Hwee and Mansur, 1996).

in flexure and sufficient depth to provide efficient shear reinforcement.

Openings should not be positioned closer than one-half the beam depth D to the supports in order to avoid the critical region for shear failure and reinforcement congestion. Moreover, positioning of an opening closer than 0.5 D to any concentrated load should be avoided. Depth of the openings should be limited to 50% of the overall beam depth. When multiple openings are used, the post separating two adjacent openings should not be less than 0.5 D to insure that each opening behaves independently.

DESIGN SPECIFICATION OF BEAMS WITH SMALL OPENINGS

In their book entitled “Concrete beams with opening”, Mansur and Kiang-Hwee (1999) represented the following procedures to obtain the ultimate moment capacity of solid beams and beams with openings. The openings that are circular, square, or nearly square in shape may be considered as small openings provided that the depth (or diameter) of the opening is less than 40% of the overall beam depth. Hence, the analysis and design of a beam with small openings may follow the course of action similar to that of a solid beam. First, a solid beam that is subject to pure bending is assumed. Finally, the beam will exhibit a well-developed pattern of cracks, as shown in Figure 3(a). According to the usual flexural strength theory, the strain and stress distributions across a section at ultimate state are shown in Figure 3(b). The tensile stress resultant, T, and the compressive stress resultant, C, form a couple exactly equal to the applied moment at collapse.

If the beam section shown in Figure 3(b) is assumed to be under-reinforced, that is, the steel reinforcement yields at failure, and if the actual compressive stress block at nominal bending strength is replaced by Whitney's equivalent rectangular stress block, then T and C may be obtained as follows:

$$T = A_s f_y \tag{6}$$

$$C = 0.85 f'_c ba \tag{7}$$

Where:
A_s = area of tensile reinforcement,
f_y = yield strength of tensile reinforcement,
f'_c = cylinder compressive strength of concrete,
b = width of the section, and
a = depth of rectangular compressive stress block.
The horizontal equilibrium, that is, C = T gives

$$a = \frac{A_s f_y}{0.85 f'_c b} \tag{8}$$

The nominal flexural strength, M_n is then obtained from moment equilibrium as:

$$M_n = A_s f_y (d - \frac{a}{2}) \tag{9}$$

Which on substituting Equation (8), reduces to

$$M_n = A_s f_y (d - 0.59 \frac{A_s f_y}{f'_c b}) \tag{10}$$

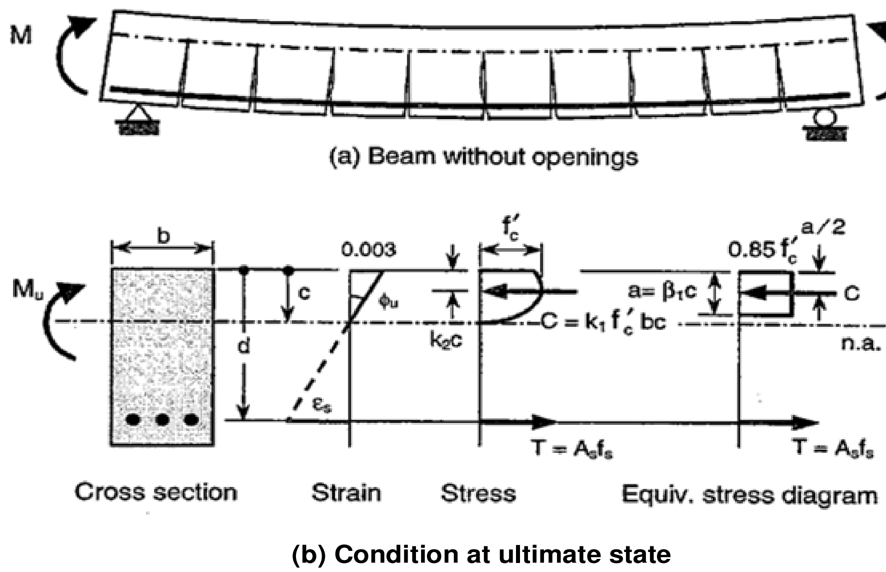


Figure 3. Beam subjected to pure bending (Mansur and Kiang-Hwee, 1999).

Now, as shown in Figure 4(a), consider that a transverse opening of any shape is introduced in the same beam.

It is worthwhile mentioning that the provision of opening does not change the load-carrying mechanism as long as the opening and the ultimate strength of the beam will not be influenced by the presence of the opening. Following the preceding discussion, there will be no reduction in the ultimate moment capacity of the beam if the minimum depth of the compression chord, h_c, is greater than or equal to the depth of compressive stress block, a, that is, when

$$h_c \geq \frac{A_s f_y}{0.85 f_c^{'} b} \tag{11}$$

Beams are usually subject to combined bending and shear. Figure 5(a) shows a simply-supported, reinforced concrete beam with an opening, subject to a concentrated load at a distance x from the support on the same side of the opening. The free-body diagram at the beam opening can be represented as in Figure 5(b), and the free-body diagrams of the chord members above and below the opening as in Figure 5(c). It is observed that the unknown action effects at the center of the opening are the axial forces (N_t and N_b), the bending moments (M_t and M_b), and the shear forces (V_t and V_b) in the chord members. There are three equilibrium equations relating these six unknowns. They are:

$$M_t + M_b + NZ = M_m \tag{12}$$

$$N_t + N_b = 0 \tag{13}$$

$$V_t + V_b = V_m \tag{14}$$

In which M_m and V_m are the applied moment and shear force, respectively, at the center of the opening. Thus, the beam is statically indeterminate to the third degree.

DESIGN SPECIFICATION OF BEAMS WITH LARGE OPENINGS

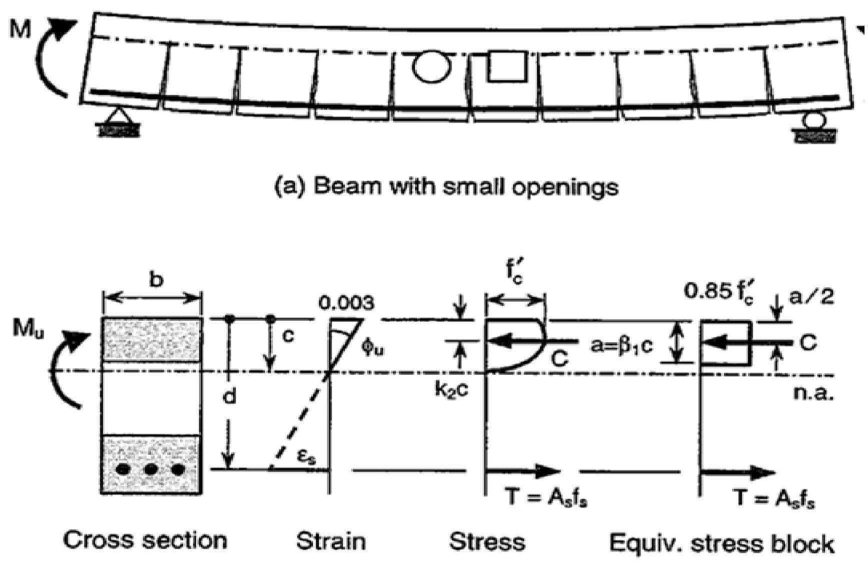
Kiang-Hwee and Mansur (1996) also proposed a simple design procedure for reinforced concrete beams with large web openings as shown subsequently.

Design solid segment

The solid segments of the beam can be designed in usual manner if the bending moment and shear force envelopes are considered. Consistent with the test results, contra flexure points are considered at mid-span of the chord members for which the axial load is obtained by dividing the beam moment at the center of the opening by the distance between the plastic centroids of the chord members.

Design chord members

Force and moment in chord members: As it is shown in Figure 6, they determine the ultimate design bending moment M_m and shear force V_m at the middle of the opening segment from bending moment and shear force envelopes, and calculate axial forces N_t and N_b (positive



(b) Condition through the opening at ultimate state

Figure 4. Beam with openings under pure bending (Mansur and Kiang-Hwee, 1999).

for compression) acting, respectively, in the top and bottom chords.

$$N_t = \frac{M_m}{Z} \tag{15}$$

$$N_b = -N_t \tag{16}$$

Where, z is the distance between the plastic centroids of the top and bottom chords. Distribute the applied shear between the top and bottom chord as:

$$V_t = V_m\left(\frac{I_{gt}}{I_{gt} + I_{gb}}\right) \tag{17}$$

$$V_b = V_m\left(\frac{I_{gb}}{I_{gt} + I_{gb}}\right) \tag{18}$$

I_{gt} and I_{gb} are the gross moment of inertia of top and bottom chords, respectively.

Calculate moment at the ends of chord members from statics (Figure 6).

$$M_1 = \frac{-wl^2}{8} - \frac{v_t l_0}{2} \tag{19}$$

$$M_2 = \frac{-wl^2}{8} + \frac{v_t l_0}{2} \tag{20}$$

$$M_3 = -\frac{v_b l_0}{2} \tag{21}$$

$$M_4 = \frac{v_b l_0}{2} \tag{22}$$

Design of reinforcements for chords

Design of longitudinal reinforcement for chord members

The longitudinal reinforcement in the top and bottom of the solid section adjacent to the opening should be continued throughout the opening segments. Additional reinforcement is required to resist the combined moment, and axial force in each chord member is designed as well. As a trial, each chord is symmetrically reinforced in such a situation.

Design of shear reinforcement for chord members

The shear reinforces carried by the top and bottom chords are given by Equations 17 and 18, respectively. Considering these forces, the required amount of reinforcement can be designed in a manner similar to the reinforced concrete beams and slabs.

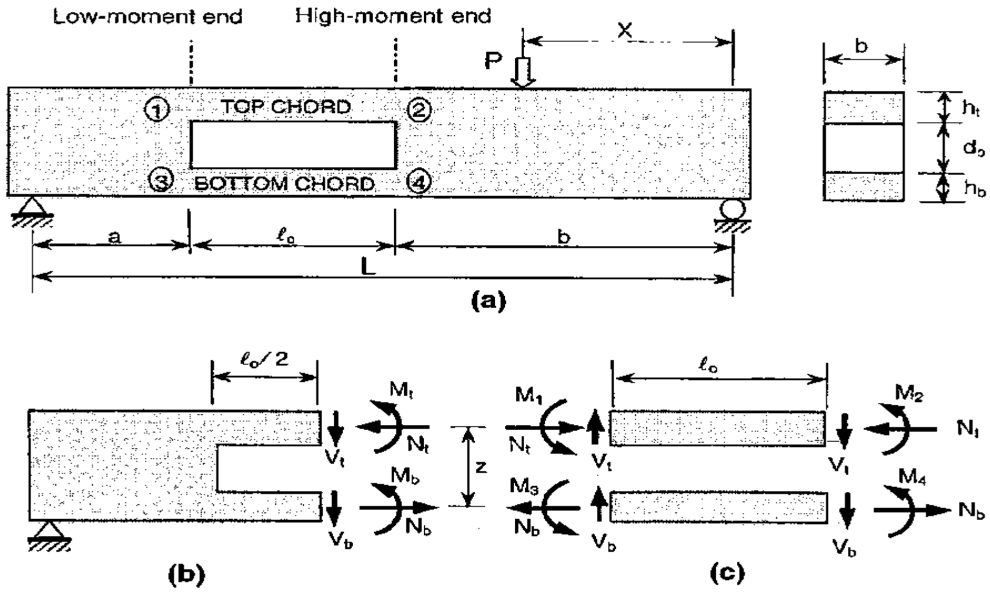


Figure 5. Beam with an opening under bending and shear: (a) The beam, (b) Free-body diagram at opening; (c) Free-body diagram of the chords (Mansur and Kiang-Hwee, 1999).

Design of post between the openings

The post should be designed as a solid segment to carry the total applied shear. The contribution of the corner reinforcement at the two adjacent openings should be ignored.

SERVICABILITY RESTRICTIONS FOR CHECKING THE DESIGN

Two important requirements should be met for designing the serviceability. They are cracking and deflection.

Cracking

Considering this fact that crack control requirements of the solid segments are provided either by proper reinforcement detailing or by physical calculation, the following crack control provisions are recommended for critical sections at corners of the opening. At each vertical edge of the opening, a combination of vertical stirrups and diagonal bars will be used with a shear concentration factor η of 2. For each side of the opening, the required area of vertical stirrups A_v is given by:

$$A_v = \frac{0.25(\eta . v)}{\phi . f_{yv}} \quad (23)$$

In which V, φ, and f_{yv} are the design shear, capacity reduction factor and yield stress of stirrups, respectively. The vertical stirrups should be placed as close to the edge of the opening as permitted by the required concrete cover. The required area of diagonal reinforcement A_d is given as:

$$A_d = \frac{0.75(\eta . v)}{\phi . f_{yd} . \sin\phi} \quad (24)$$

Where f_{yd} is the yield stress and φ is the angle of inclination of diagonal bars to the beam axis. The same amount of diagonal reinforcement should be provided both at the top and bottom corners of the opening in order to avoid confusion during construction and to account for any possible load reversal.

Deflection

The indirect way of satisfying the serviceability

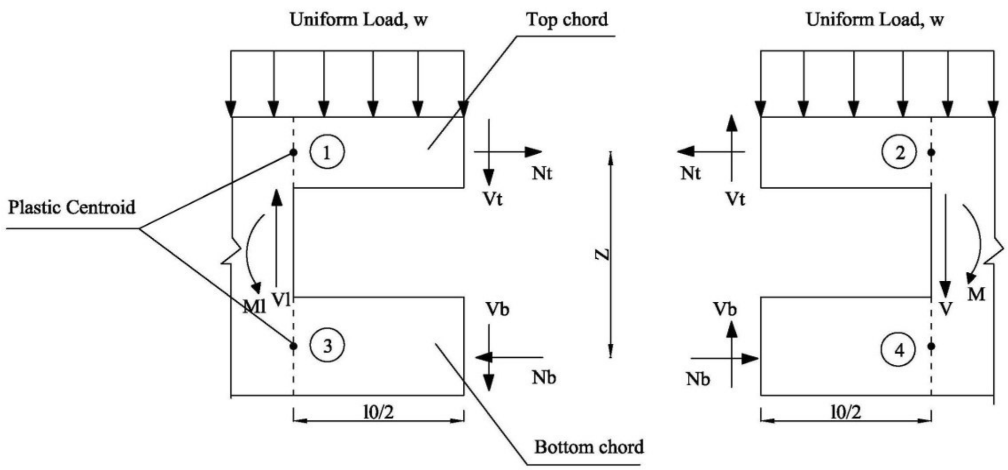


Figure 6. Free-body diagram of opening segment (Kiang-Hwee and Mansur, 1996).

requirement of deflection by limiting the span- effective depth ratio is not valid for a beam with openings. Therefore, an estimate of the actual service load deflection is necessary.

DESIGN SPECIFICATION OF HIGH STRENGTH CONCRETE DEEP BEAMS

Tan et al. (1995, 1997, 2003) and Leong and Tan (2003) explored the effects of high strength, shear span to depth ratios and web reinforcement ratios of the beams employing both experimental programs and numerical analyses. The design formula for high strength concrete deep beams is:

$$v_n = \frac{1}{\frac{\sin 2\theta_s}{f_t A_c} + \frac{1}{f_c A_{str} \sin\theta_s}} \tag{25}$$

Where:

$$f_t = 2A_s f_y \frac{\sin\theta_s}{\frac{A_c}{\sin\theta_s}} + 2A_w f_{yw} \frac{\sin(\theta_s + \theta_w)}{\frac{A_c}{\sin\theta_s}} \frac{d_w}{d} + f_{ct} \tag{26}$$

And

$$\tan\theta_s = \frac{(h - \frac{l_a}{2} - \frac{l_c}{2})}{a} \tag{27}$$

in which;

θ_s = angle between the longitudinal tension reinforcement and the diagonal strut,

f_t = combined tensile strength of reinforcement and concrete,

A_c = area of concrete section,

A_{str} = cross-sectional area of diagonal strut,

f_y = yield strength of longitudinal steel reinforcement,

A_w = area of web reinforcement,

f_{yw} = yield strength of web reinforcement,

θ_w = angle between the web reinforcement and the axis of beams at the intersection of the reinforcement and diagonal strut,

d_w = distance from the beam top to the intersection of the web reinforcement with the line connecting the support centre and the load centre,

d = effective depth,

f_{ct} = tensile strength of concrete,

h = overall height of deep beam,

l_a = height of bottom node,

l_b = width of support bearing plate, and

a = shear span measured between concentrated load and support point.

RESULTS AND DISCUSSION

For investigating the verification of existing Equation 16 beam were examined by Yoo et al. (2003) has been selected then experimental results are compared to results obtained by corresponding formula, the proportion of comparison and details are shown in Table 1. As it is obviously seen in the Table 1, none of equations have reasonable accuracy in predicting of ultimate load for corresponding beams. For example the ratio relate to Equation (2) with mean of 0.8, underestimates bearing capacity of beams. It is caused by term that, this term is concerned with the position and size of the web opening. Since the opening size increases and approaches to the base of the beam, this term will produce negative value. Finally, proportions related to verification of Equation 25

Table 1. Comparison the experimental and equation results.

Specimen	Calculation	Results (Kn)	Experiment	
	Equation (2)	Equation (25)	Equation (2)	Equation (25)
RO40-150	146.76	93.53	1.67	1.06
RO40-180	105.64	92.78	1.22	1.07
RO40-210	68.12	93.17	0.86	1.17
RO40-240	23.67	91.76	0.33	1.27
RO80-150	68.71	176.46	0.55	1.41
RO80-180	52.66	163.31	0.57	1.75
RO80-210	35.28	145.10	0.43	1.76

are more than 1 which guesses overestimate failure load which could be due to the fact that the equation does not consider the effect of concrete of such a high strength.

Conclusions

Several analytical researches carried out by previous researchers on concrete beems with small and large opening, deep beams and rectangular concrete beams with web openings were reviewed in this paper; however, more evaluation of behavior for concrete beam with web openings is needed to gain more efficient and reasonable methods for designing and construction. The analyzed research studies provided several practical results. Moreover, many equations were represented to design and analyze the RC beams with small and large openings.

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